Irradiation and Annealing of Silicon Planar Transistors

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to the Faculty of Science of the University of Basle

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(Dean of the Faculty)

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IRRADIATION AND ANNEALING OF SILICON PLANAR TRANSISTORS

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Abstract—The effects of irradiation by fast neutrons (14 MeV) and by gammas (Co^{60}) on collector cutoff current I_{CBO} and base current I_B at low current densities were investigated on silicon planar transistors. With neutron irradiation I_{CBO} and I_B increase linearly, while with gamma irradiation saturation occurs. The temperature dependence of I_{CBO} between 9 and 89°C shows that the recombination level of the induced defects lies in the middle of the forbidden gap.

Moreover, gamma irradiation introduces slow surface states, which are responsible for an observed I_{CBO} drift. The measured base currents can be described by the equation

$$I_B = \text{const.} \exp(E_b/kT) \exp(qV_{EB}/nkT).$$

It was observed that $n = 1{\cdot}27$; $E_b = 0{\cdot}95$ eV after neutron irradiation and $n = 1{\cdot}8$; $E_b = 0{\cdot}68$ eV after gamma irradiation. The result of neutron irradiation cannot be explained by any of the existing theories. Based upon our measurements we conclude that neutrons induce defects within the volume of the transistors, while the consequences of gamma irradiation are explained by surface effects.

All of the observed radiation damages can be completely annealed. Annealing for gamma damage proceeds in one stage at 100°C and that for neutron damage in two stages at 120°C and 270°C respectively. For the first annealing stage of neutron irradiated transistors an activation energy of

$$E_a = 1{\cdot}53 \pm 0{\cdot}07 \text{ eV}$$

was measured. In many cases certain properties of *npn* transistors may be improved by irradiation and annealing.

Résumé—Les effets de l'irradiation par neutrons rapides (14 MeV) et par rayons gamma (Co^{60}) sur le courant collecteur de rupture I_{CBO} et sur le courant de base I_B des transistors de silicium plans ont été examinés à de basses densités de courant. Avec l'irradiation par neutrons, I_{CBO} et I_B augmentent linéairement tandis qu'avec l'irradiation gamma la saturation se produit. La dépendance de température de I_{CBO} entre 9 et 89°C démontre que le niveau de recombinaison des défauts ainsi induits se trouve au milieu de l'intervalle interdit.

Aussi, l'irradiation gamma introduit des états de surface lents qui sont responsables de l'apport de I_{CBO} observé. Les courants de base mesures peuvent être décrits par l'équation

$$I_B = \text{const.} \exp(E_b/kT) \exp(qV_{EB}/nkT).$$

On a observé que $n = 1{,}27$ & $E_b = 0{,}95$ eV après l'irradiation par neutrons et $n = 1{,}8$ & $E_b = 0{,}68$ eV après l'irradiation gamma. Les résultats de l'irradiation par neutrons ne peuvent être expliqués par aucune théorie en existence. Nous basant sur nos mesures, nous concluons que les neutrons induisent des défauts dans le volume des transistors, tandis que les conséquences de l'irradiation gamma sont expliqués par les effets de surface.

Tous les endommagements de radiation observés peuvent être complètement recuits. La recuite pour les endommagements gamma procède en une étape à 100°C et pour les endommagements à neutrons en deux étapes à 120 et 270°C respectivement. Pour la première étape des transistors irradiés par neutrons, une énergie d'activation de

$$E_a = 1{,}53 \pm 0{,}07 \text{ eV}$$

a été mesurée. Dans plusieurs cas, certaines propriétés des transistors *npn* peuvent être améliorées par irradiation et recuite.

Zusammenfassung—Der Einfluss von schnellen Neutronen (14 MeV) und von Gammastrahlen (Co^{60}) auf den Kollektor-Sperrstrom I_{CBO} und auf den Basisstrom I_B (bei kleinen Stromdichten) wurde an Silizium-Planar-Transistoren untersucht. I_{CBO} und I_B nehmen mit der Neutronenbestrahlung linear zu, während bei Gammabestrahlung Sättigung eintritt. Die Temperaturabhängigkeit des I_{CBO} zwischen 9° und 89°C zeigt, dass die Rekombinationsniveau der erzeugten Störstellen in der Mitte der verbotenen Zone liegen. Zusätzlich erzeugt Gammabestrahlung langsame Oberflächenzustände, die für eine beobachtete Drift des I_{CBO} verantwortlich sind.

Die gemessenen Basisströme I_B können durch die Gleichung

$$I_B = \text{const.} \exp(E_b/kT) \exp(qV_{EB}/nkT)$$

beschrieben werden. Nach Neutronenbestrahlung wird $n = 1{,}27$; $E_b = 0{,}95$ eV nach Gammabestrahlung $n = 1{,}8$; $E_b = 0{,}68$ eV beobachtet. Das Verhalten nach Neutronenbestrahlung kann mit keiner der bekannten Theorien erklärt werden. Aus unseren Messungen schliessen wir, dass Neutronen Störstellen im Volumen des Transistors erzeugen, während die Auswirkungen der Gammabestrahlung durch Oberflächeneffekte erklärt werden.

Alle beobachteten Strahlungsschäden können vollständig ausgeheilt werden. Gammastrahlungsschäden heilen bei 100°C aus, Neutronenschäden in zwei Stufen bei 120°C und bei 270°C. Für die erste Ausheilungsstufe neutronenbestrahlter Transistoren wurde eine Aktivierungsenergie

$$E_a = 1{,}53 \pm 0{,}07 \text{ eV}$$

gemessen. Gewisse Eigenschaften von *npn*-Transistoren lassen sich in vielen Fällen durch Bestrahlungen und Ausheilen verbessern.

NOTATION

A_C	collector area
$\langle c_{n,p} \rangle$	average probability of electron and hole capture respectively
D_n	diffusion constant for electrons
E_a	activation energy for defect annealing
E_b	activation energy of I_B
E_r	activation energy of I_{rg}
E_c	energy of the lowest conduction band level
E_v	energy of the highest valence band level
$E_i = (E_c+E_v-kT \log N_c/N_v)/2$	intrinsic Fermi level
$E_{g0} = 1{\cdot}21$ eV	forbidden energy gap (extrapolated to 0°K)
E_t	energy level of the recombination centres
$\epsilon_t = (E_t-E_i)/kT+\frac{1}{2}\log(\tau_{p0}/\tau_{n0})$	
h_{FB}	forward current transfer ratio (common base)
h_{FE}	forward current transfer ratio (common emitter)
h_{FEO}	temperature and current independent component of h_{FE}
I_B	base current (d.c.)
I_{Bi}	irradiation induced I_B
I_{BO}	diffusion component of base current
$I_{BR} = I_B-I_{BO}$	non-ideal component of base current
I_C	collector current
I_{CBi}	irradiation induced I_{CBO}
I_{CBO}	collector cutoff current (d.c., emitter open)
$I_{CO} = I_C-I_{CBO}$	diffusion component of collector current
I_S	Shockley saturation current (diffusion component of I_{CBO})
I_{Si}	irradiation induced I_S
I_{rg}	recombination–generation current (space charge layer generated component of I_{CBO})
I_{rgi}	irradiation induced I_{rg}
k	Boltzmann constant
L_n	diffusion length for electrons in p-region
m	exponent of the I_{rg}/V_{CB}—characteristic [equation (3)]
n	exponent in the base current characteristics [equation (5)]
n_i	density of electrons or holes in intrinsic silicon
N_c, N_v	effective density of levels in the conduction and valence band respectively
N_t	density of recombination centres
N_{t0}	density of recombination centres before annealing
$n_p = n_i^2/p_p$	density of electrons in p-type material
q	magnitude of electronic charge
T	temperature
τ_{p0}	lifetime for holes in highly n-type silicon
τ_{n0}	lifetime for electrons in highly p-type silicon
$\tau_0 = \sqrt{(\tau_{n0}\tau_{p0})}$	
V_{CB}	collector to base voltage

V_{EB}	emitter to base voltage
w	thickness of transistor base region
W	width of space charge layer

1. INTRODUCTION

RADIATION damage research in semiconductor devices can be approached from two points of view. From one standpoint it is of interest how much radiation a transistor or diode may absorb before it malfunctions.[1] The alternate approach employs the semiconductor device for fundamental investigations of radiation damage in silicon and germanium.[2]

In this paper a combination of these two points of view is attempted. Silicon planar transistors are irradiated by neutrons and gammas. The data obtained are applicable to most types of planar transistors, if allowance is made for differences in geometry and in doping. By measuring the temperature dependence of the collector cutoff current the recombination level of the induced defects could be ascertained. There is strong evidence that neutron and gamma irradiation produce different defects at different locations of the transistor structure. In all transistors studied the base current obeyed a simple analytical law, which cannot be explained theoretically. Isochronal annealing experiments reveal distinct annealing stages.

2. EXPERIMENTAL PROCEDURE

(*a*) *Transistors*

Unless otherwise noted all investigations were carried out on SGS 2 N 1893—transistors, which are high voltage *npn* double diffused silicon planar transistors. All numerical results are averages of measurements on several transistors. Some unpredicted results have been verified on the SGS 2N1893 and other planar transistors (NPN: SGS 2N1613, SGS 2N2484, SGS 2N1983, SGS 2N708, TI 2N1893, Mot MM1613; PNP: SGS 2N1132, Mot MM1614).

Unfortunately no direct information about the dopants and their concentrations is available. Most probably *P* and *B* have been used for the diffusion. Since no significant differences are observed between the investigated types of transistors (*npn* and *pnp*), with the exception mentioned in Section 5(*c*), the results seem to apply to *p*- and *n*-type bases.

(*b*) *Irradiation*

The transistors have been irradiated by 14 MeV neutrons (*d–t* reaction) on a 160 keV-accelerator. The relative integrated neutron flux was monitored by a scintillation counter with an accuracy of ± 2 per cent. Absolute calibration to within a factor 2 was attained from phosphor activation. Gamma irradiation was carried out with a 90 c Co^{60}-source. At a distance of 1·5 cm the transistors were exposed to a flux of

$$(1{\cdot}4 \pm 0{\cdot}1)10^{13} \text{ photons/cm}^2 \text{ min}$$

$[(1{\cdot}9 \pm 0{\cdot}1)10^4$ r/min$]$.* Two transistors, which were used for isochronal annealing measurements, were irradiated by a 3000 c Co^{60}- source. All irradiations were performed at room temperature.

(*c*) *Annealing*

The transistors were annealed in an oven over a temperature range 40 to 300°C with a precision of $\pm 0{\cdot}5°$. Isochronal annealing curves were measured in 10°-steps, 1 hr at each temperature. For isothermal annealing a lead brick with transistor size holes, filled with oil, was placed in the oven. To shorten warm up time the transistors were inserted into these holes. To correct the annealing time for warm up and cool down periods, the temperature of the silicon crystal was monitored by measuring I_{CBO}. Both annealing and I_{CBO} depend exponentially on temperature. Since the activation energies of these two processes

$$(T > 100°\text{C})$$

are not very much different, I_{CBO} is used for the analog computation of the correction. Integration of the I_{CBO} vs. time curve yields the correction after allowance is made for the differences in activation energies. Prior to irradiation all transistors have been annealed at 300°C for at least 24 hr. This treatment did not change I_{CBO} by more than 5 per cent (typically it decreased by 2 per cent).

(*d*) *Measurement of I_{CBO}, I_B and I_C*

The transistors were immersed in an oil bath,

* The Compton cross-section for Si is about $1{\cdot}5 \times 10^{-1}$ cm^{-1}. Each of the Compton electrons (mean energy 30 eV) produces between 1 and 3 lattice defects. From this we conclude a defect production rate of 0·3 (defects/cm^3)/photon.

the temperature of which was variable from 8 to 170°C with an error of ±0·1°. Unless otherwise noted all measurements were made at 31°C (including all measurements of the annealing investigations). To obtain the collector cutoff current I_{CBO} an electrometer amplifier in a current compensation circuit has been employed for null detection. With this arrangement I_{CBO} could be measured down to 10^{-12} A with an error of ±0·3 per cent. However, the temperature variations of the oil bath limited the accuracy to ±0·5 per cent. The base current I_B was calculated from measured values of the common base current transfer ratio h_{FB} ($V_{CB} = 0$). The probable error on I_B is ±5 per cent for currents $\geqq 10^{-7}$ A. For this calculation the collector current I_C as a function of the emitter to base voltage V_{EB} is needed. The collector diffusion current, $I_{CO} = I_C - I_{CBO}$, was not influenced by the integrated neutron or gamma fluxes used in this experiment. Our measurements are in excellent agreement with the diffusion theory first given by SHOCKLEY.[3] The slopes of log I_{CO} vs. V_{EB} (T = const.) are equal to q/kT within 1 per cent over more than six decades. From the plot of log $(I_{CO}T^{-2})$* vs. T^{-1} (V_{EB} = const.) we obtain $E_{g0} = 1{\cdot}214 \pm 0{\cdot}03$ eV.

3. NEUTRON IRRADIATION

(a) *Collector cutoff current* I_{CBO}

I_{CBO} is the reverse current of the collector-base diode. It consists of the recombination–generation current I_{rg} and of the Shockley saturation current I_S, which is voltage independent

$$(I_{CBO} = I_{rg} + I_S).$$

In silicon diodes at room temperature I_{rg} greatly exceeds I_S. SAH *et al.*[4] derived the following relation for the recombination–generation current†.

$$I_{rg} = qWn_iA_C \left[2\sqrt{(\tau_{p0}\tau_{n0})}\cosh\left(\frac{E_t - E_i}{kT} + \frac{1}{2}\log\frac{\tau_{p0}}{\tau_{n0}}\right)\right]^{-1} \quad (1)$$

(see notation for definition of terms in this and the following equations.)

According to the recombination statistics of SHOCKLEY and READ[5]:

$$\tau_{p0} = (N_t\langle c_p\rangle)^{-1} \qquad \tau_{n0} = (N_t\langle c_n\rangle)^{-1} \quad (2)$$

Therefore I_{rg} is proportional to the number N_t of recombination centres. Since neutron irradiation generates recombination centres, we expect I_{CBO} to increase linearly with integrated neutron flux. Experimental results, given in Fig. 1, confirm this assumption. On the average we find that 10^{11} nvt cause an increase in I_{CBO} of $13 \pm 1{\cdot}4\ 10^{-12}$ A.

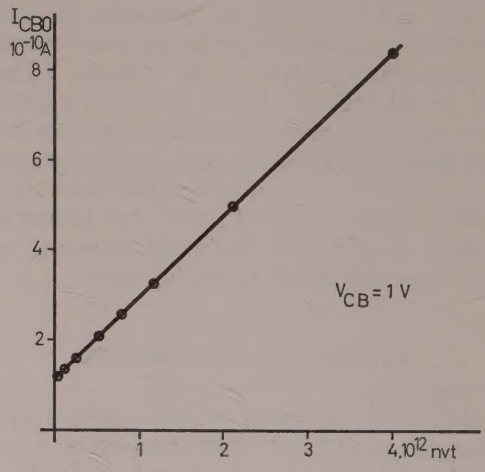

FIG. 1. Reverse current I_{CBO} vs. integrated neutron flux (all results displayed in figures are from measurements on SGS 2N1893-transistors). T = 31°C.

In equation (1) only the junction width W depends on the voltage V_{CB}. Therefore I_{rg} increases with voltage V_{CB} corresponding to the increase in junction width. The reverse characteristic of silicon diodes normally has the form:

$$I_{rg} = \text{const.} \qquad V^m (0{\cdot}3 \leqslant m \leqslant 0{\cdot}5) \quad (3)$$

In most of the junctions studied we found $m \cong 0{\cdot}6$, which is characteristic of oxidized p–n^+-junctions, as has been shown by EDAGAWA

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* According to SHOCKLEY:[3]

$$I_{CO} = (qn_pD_n/L_n)\exp(qV_{EB}/kT)\,\mathrm{csch}(w/L_n)$$
$$\cong (qn_pD_n/w)\exp(qV_{EB}/kT)$$
$$\sim T^2\exp(-E_{g0}/kT + qV_{EB}/kT)$$

The temperature dependence of the diffusion constant D_n was assumed to be as T^{-1}.

† We wish to point out an error in Appendix III of the SAH *et al.* paper.[4] In calculating equation (49) an error in the analysis has occured, as SAH confirmed by private communication. In order to obtain the activation energy log$(I_{rg}T^{-3/2})$ should be plotted instead of log$(I_{rg}T^{-5/2})$.

et al.[6]. This high value of m is due to the inversion layer formed below the oxide on the p-side of the junction. The distribution of doping in the junction and at the surface determines the exact value of m. It should be temperature independent.

However, at higher temperature ($T > 50°C$) the Shockley saturation current I_S has to be taken into account. From measurements at $T \geqslant 120°C$, where I_{rg} is negligible, we may extrapolate I_S to lower temperature. In the temperature range below 90°C no difference in the reverse collector current could be experimentally observed between open or short circuited emitter base connections. Therefore the saturation current I_S with open or with short circuited emitter, which differ at $T \geqslant 120°C$, may be used for the extrapolation. The short circuit saturation current $I_S(V_{EB} = 0)$ was used because of its well known dependence on the temperature. It is to a good approximation proportional to $T^{-2} \exp(E_{g0}/kT)$.[3] This was confirmed experimentally. By subtracting the extrapolated values of I_S from the measured values of I_{CBO} we find I_{rg}-characteristics of the form V^m for temperatures up to 90°C. As expected the characteristic exponent m is within experimental error independent of temperature.

The analysis of the reverse current I_{CBi} of irradiated transistors cannot be carried out the same way. (The subscript i stands for irradiation induced currents.) Unfortunately it is not possible to measure I_S of irradiated transistors, due to the annealing of neutron damage above 100°C. An analogous correction, however, is possible. At each temperature a suitable voltage independent value I_{Si} is subtracted from I_{CBi}, such that the remaining current characteristic has the expected V^m-form. It is supposed, that in this way I_{CBi} is separated in its saturation component I_{Si} and the recombination component I_{rgi}. As expected, the values of I_{Si} depend exponentially on temperature.

In Fig. 2 we plotted the irradiation generated reverse current. I_{rgi} is calculated from the difference of I_{CBO} after irradiation and I_{CBO} before irradiation with the above mentioned correction for I_{Si}. The fact, that m is not changed appreciably by irradiation for all transistors tested

$$(0{\cdot}3 \leqslant m \leqslant 0{\cdot}6)$$

indicates, that the neutron irradiation induced I_{CBi} originates in the same regions as the I_{CBO} of the unirradiated transistor. Neutron damage therefore seems to be uniformly distributed in all parts of the transistor structure. The level E_t of the recombination centres can be obtained by plotting the log of the reverse current as a function of the reciprocal temperature at constant reverse bias V_{CB} ($V_{CB} > 5\ kT/q$).

$$E_r = \frac{\mathrm{d}}{\mathrm{d}T^{-1}} \log(I_{rg} T^{-3/2}) = -\frac{1}{2} E_{g0} \quad (4)$$

$$-(E_t - E_i) \tanh \epsilon_t$$

$$\epsilon_t = \frac{E_t - E_i}{kT} + \frac{1}{2} \log \frac{\tau_{p0}}{\tau_{n0}}$$

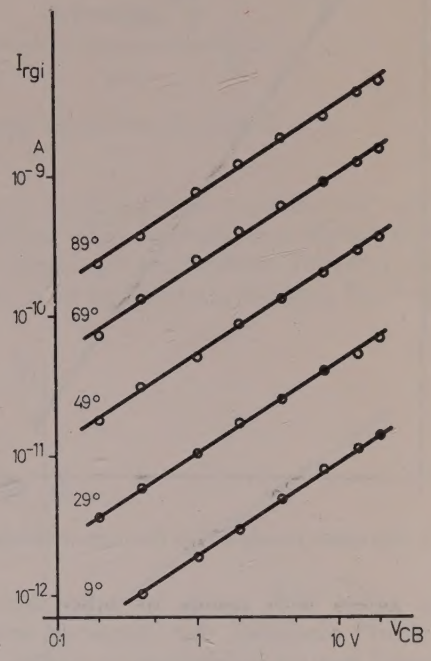

FIG. 2. Voltage characteristic of I_{rgi} (neutron irradiation).

We obtain:

$$E_r = 0{\cdot}654 \pm 0{\cdot}01 \text{ eV (irradiated trans., Fig. 3)}$$

$$(E_t - E_i) \tanh \epsilon_t = 0{\cdot}049 \pm 0{\cdot}01 \text{ eV}$$

$$E_r = 0{\cdot}607 \pm 0{\cdot}01 \text{ eV (unirradiated trans.)}$$

$$(E_t - E_i) \tanh \epsilon_t = 0{\cdot}002 \pm 0{\cdot}01 \text{ eV}$$

Since we do not know τ_{p0}/τ_{n0}, an exact calculation

of E_t is not possible.* It can be said, however, that E_t lies close to the middle of the forbidden energy gap. This result is not surprising because, due to the factor $(\cosh \epsilon_t)^{-1}$, recombination centres are most effective for $\epsilon_t = 0$. A uniform distribution of energy levels over the energy gap

$$(\langle c_{n,p} \rangle = \text{const.})$$

yields $E_r = -E_{g0}/2 - kT$, a value which is close to our results.

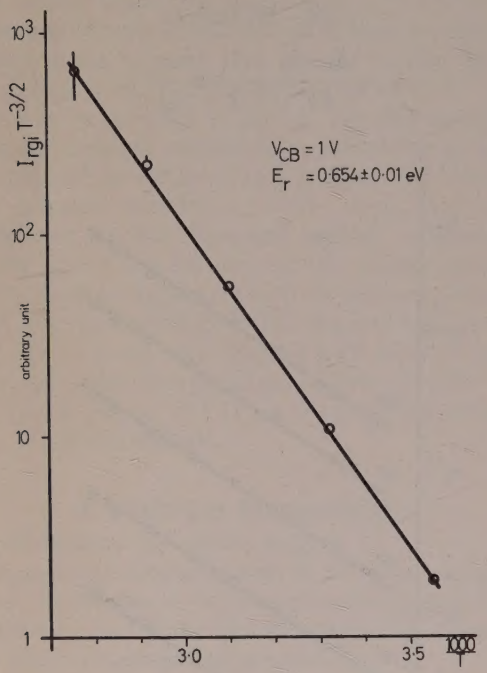

FIG. 3. Activation energy of I_{rgi} (neutron irradiation).

This agrees with results by other authors: WERTHEIM[7] concluded, that lifetime in neutron bombarded material is dominated by centres near the middle of the energy gap. By studying low frequency-noise in junction field effect transistors, LAURITZEN[8] found that neutron irradiation creates a distribution of recombination levels near the centre of the energy gap. From studies on MOS-structures GROVE *et al.*[9] concluded, that in the depletion region minority carrier recombination proceeds over levels near the centre of the energy gap. Our results disagree with lifetime measurements by BECK *et al.*[10] They can be compared only with measurements of the temperature dependence of the minority carrier lifetime. Other methods are sensitive to recombination levels in different parts of the forbidden energy gap.

(b) Base current I_B

Non-ideal diode currents have been the topic of considerable discussion. We refer to all diode current components with the exception of the Shockley diffusion current as non-ideal. In a transistor (*npn*) the electron component of the diffusion current flows from emitter to collector. The hole component, which is very small compared to the electron component, and all non-ideal components of the emitter diode current constitute the base current. For this reason the transistor is particularly suited to study non-ideal diode currents. For a complete discussion of the diode current components we refer to SAH.[11] He differentiates four current components, which all can be approximately described by an exponential law of the form:

$$I = \text{const.} \exp(qV/nkT) \qquad (5)$$

The components are as follows: (*a*) bulk diffusion current ($n = 1$) (*b*) bulk recombination current ($n \simeq 2$) (*c*) surface recombination current ($n \simeq 2$) (*d*) surface channel current ($2 \leqslant n \leqslant 4$).

Our base current I_B also conforms to this exponential law. We obtain values of n between 1·1 and 1·8. It appears that n varies with temperature. There is, however, a correction to be made: at higher temperature ($T \geqslant 140°C$) h_{FE} reaches a temperature and nearly current independent value h_{FEO}. This corresponds to a base current

$$I_{BO} = (1/h_{FEO})I_C.$$

I_{BO} might be any current which is proportional to the density of minority carriers at the emitter junction. I_{BO} is most likely the hole diffusion current flowing from base to emitter. At 30°C I_{BO} is smaller than 5 per cent of I_B in the range of V_{EB} considered. No change in I_{BO} by irradiation has been observed.

Plotting $I_{BR} = I_B - I_{BO}$ vs. V_{EB} at different temperatures we obtain a temperature independent value of n. The plot of log I_{BR} vs. $1/T$ (V_{EB} = const.) happens to be a straight line. This means

* Because it enters logarithmically, the influence of the τ_{p0}/τ_{n0}-ratio is small.

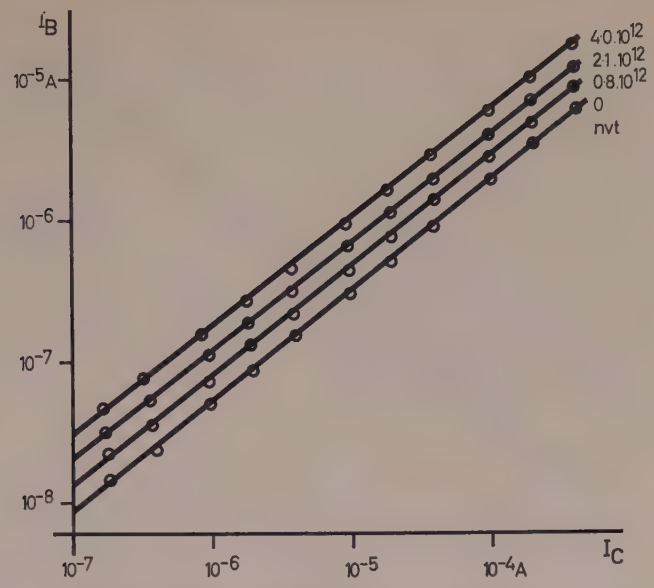

FIG. 4. Base current I_B vs. collector current I_C (neutron irradiation).

that the base current component I_{BR} can be described by:

$$I_{BR} = \text{const.} \exp(-E_b/kT) \exp(qV_{EB}/nkT) \quad (6)$$

$$E_b = 0{\cdot}950 \pm 0{\cdot}02 \text{ eV}$$

$$n = 1{\cdot}23 \pm 0{\cdot}1$$

For some 2N1893 transistors and a few of the other types studied (2N1613, 2N1983) we found:

$$E_b = 0{\cdot}75 \pm 0{\cdot}1 \text{ eV}$$

$$n = 1{\cdot}65 \pm 0{\cdot}1$$

Considering $I_C = \text{const.} \exp(qV_{EB}/kT)$ we find $I_{BR} = \text{const.} I_C^{1/n}$. In Fig. 4, log I_B is plotted vs. log I_C for different integrated neutron fluxes. I_B increases linearly with the integrated neutron flux (Fig. 5). This leads to the conclusion, that I_B is inversely proportional to the carrier lifetime τ_0. As mentioned above, the emitter to collector diffusion current I_{CO} is not influenced by the integrated neutron and gamma fluxes used. This means, that the increase of base layer recombination by irradiation is negligible at low collector currents, and that enhancement of non-ideal emitter currents is the cause of the increased base current. However, this characteristic cannot be readily explained by the SAH *et al.* theory[4] for recombination–generation currents, which predicts an n slightly dependent on voltage and temperature. To within the indicated error we found n is constant. For deep traps,

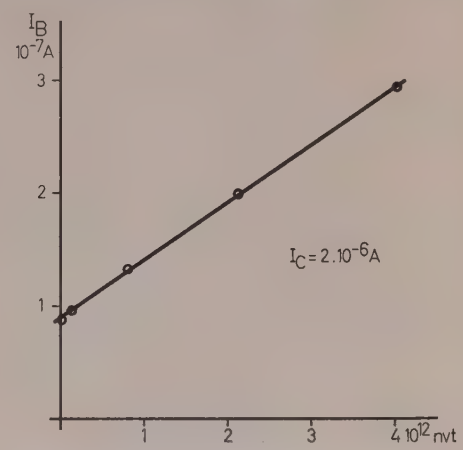

Fig. 5. Base current I_B vs. integrated neutron flux.

which were confirmed by I_{CBO} measurements, this theory yields $n \simeq 1{\cdot}8$, also in disagreement with our experiment. No explanation for the observed simple exponential law has been found. For the

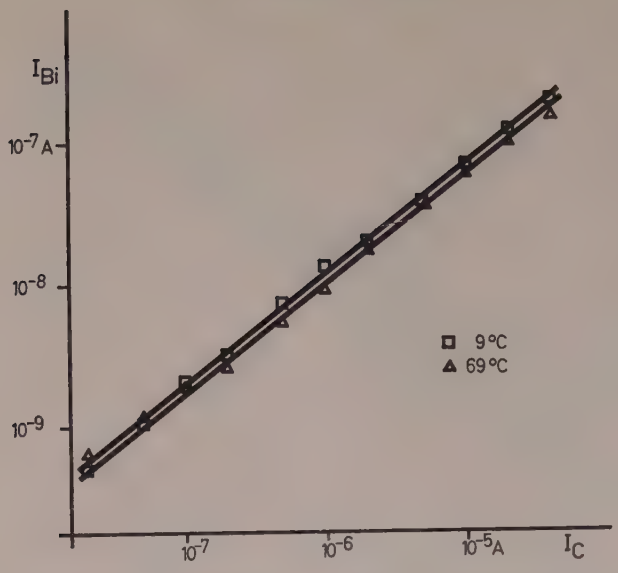

FIG. 6. Base current I_{Bi} vs. collector current I_C (neutron irradiation) (for the sake of clearness measurements at other temperatures have been omitted from the figure).

same reason no physical significance of the activation energy E_b can be given.

From the plot of the log of the irradiation generated base current I_{Bi} (I_B after irradiation minus I_B before irradiation) vs. log I_C (Fig. 6) we extracted:

$$n = 1{\cdot}27 \pm 0{\cdot}02$$

The temperature dependence of I_{Bi} (Fig. 7) indicates:

$$E_b = 0{\cdot}956 \pm 0{\cdot}01 \text{ eV}$$

These values are in agreement with those obtained from most unirradiated transistors. As mentioned, some unirradiated transistors have $n \simeq 1{\cdot}65$. Nevertheless the neutron irradiation generated base current I_{Bi} of these transistors yields the same value $n = 1{\cdot}27$.

Our results on neutron irradiated transistors will be further discussed in Section 4(*d*) together with those on gamma irradiated transistors.

4. GAMMA IRRADIATION

(*a*) *Drift of* I_{CBO}

After gamma irradiation I_{CBO} shows a drift, which begins when the reverse voltage is applied. By this drift I_{CBO} is decreased by 10–20 per cent. Analysis by exponential functions yields three time constants: 30 sec, 30 min and 7 hr, which are responsible for 15, 25 and 60 per cent of the drift respectively. When voltage is left off for a number

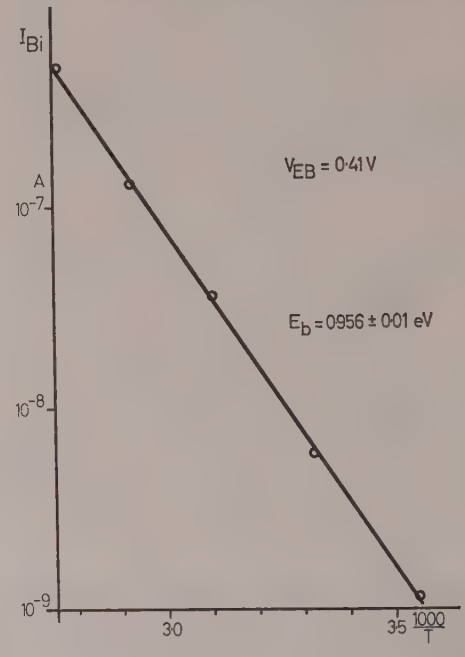

FIG. 7. Activation energy of I_{Bi} (neutron irradiation).

of days, the transistor returns to its original state and, when voltage is applied again, the same drift begins. Unfortunately the reversal of the drift could not be measured for instrumental reasons. After annealing at 200°C this drift effect disappeared.

The drift of irradiated transistors with the case evacuated or filled with paraffin does not differ from the drift described above. Neither does the drift of transistors, which were irradiated with voltage applied, differ from normal drift. Therefore this drift is not due to ion accumulation at the surface, as described by Peck *et al.*[12]

the conductance of the silicon as a function of time, when the field was applied to the surface with a voltage step (Fig. 8). The observed field effect at the oxidized surface is constant (Curve 1). After gamma irradiation ($1{\cdot}2 \times 10^{15}$ photons/cm^2, $1{\cdot}6 \times 10^6$r) conductance changes with time (Curve 2). This indicates that mobile carriers are trapped by slow surface states. After annealing (10 hr at 180°C) conductance is constant again (Curve 3). Chemical contamination from ordinary handling and cleaning did not influence the field effect. These field effect measurements prove that gamma irradiation generates slow surface states. Nothing can be

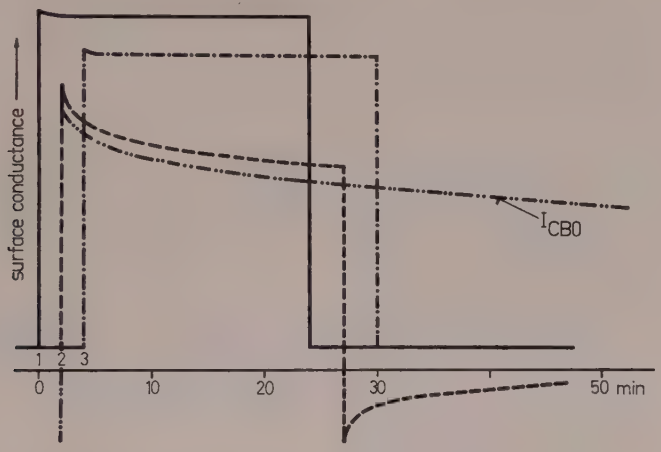

Fig. 8. Field effect on thermally oxidized silicon:
(1) before irradiation
(2) after gamma irradiation
(3) after annealing (for experimental reasons the ordinate is not exactly the same for all three curves)
— · · — · · — drift of I_{CBO} on arbitrary ordinate.

We suppose that this drift is caused by slow surface states. Therefore we have investigated the field effect[13] in thermally oxidized silicon crystals (n- and p-type, 400 Ω-cm).* The applied perpendicular electric field induces charges in the silicon. These charges are either in surface states or are mobile carriers in the layer just below the surface. The mobile carriers change the surface conductance of the silicon crystal. We have recorded

said from these experiments about the nature of these states. Motion of irradiation produced defects in the oxide produces quite a different effect.[13]

Curve 2 shows the same time dependence as the curves we obtained for the drift of I_{CBO}. In Fig. 8, I_{CBO} is indicated on arbitrary ordinate. For this reason we attribute the drift to slow surface states, which are generated by gamma irradiation.

(*b*) *Damage saturation*

I_{CBO} as well as I_B increase linearly with integrated gamma flux up to about

2×10^{14} photons/cm^2 ($2{\cdot}7 \times 10^5$ r).

* Two copper plates were closely placed on either side of a $10 \times 1 \times 0{\cdot}5$ mm Si slice, the resistivity of which was measured. The copper plates were isolated from the Si by thin polyester foils.

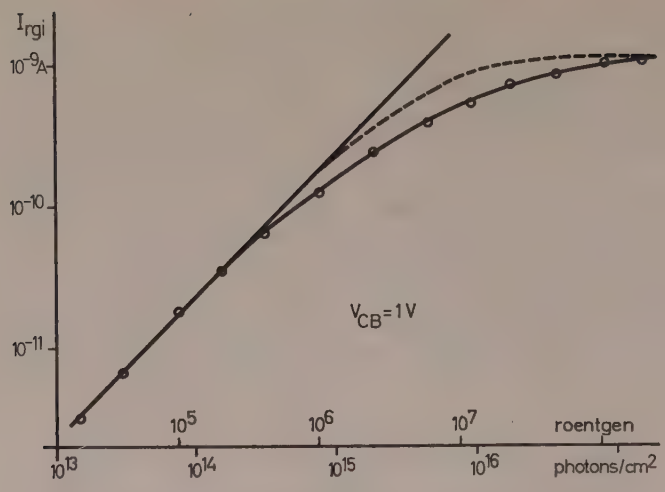

FIG. 9. Saturation of I_{rgi} with gamma irradiation ---- theoretical saturation law.

But above this integrated flux, damage curves show saturation effect (Fig. 9). The saturation curve, which is identical for I_{CBi} and I_{Bi}, cannot be matched by a normal saturation law.[14] Saturation is achieved at lower current values of I_{CBO} and I_B than those obtained by high integrated neutron fluxes. Gamma irradiation damage must therefore differ from neutron damage.

In the volume of the transistor saturation may occur for two principal reasons: (*a*) annealing by irradiation[14] (*b*) the capture cross-section of the recombination centres overlap with increasing integrated gamma flux. By neither of these processes can saturation be explained at these low current levels as a bulk effect. We believe therefore that gamma radiation damage is observed as a surface effect. Saturation could qualitatively be explained by the formation of a surface inversion layer. At higher integrated gamma fluxes not attained in this experiment one would expect to observe a bulk effect.

(*c*) *Temperature dependence of* I_{CBO}

The same type of analysis as in the case of neutron irradiation can be applied. Some added difficulties occur, however. At reverse voltages above 0·5 V the drift effect causes I_{rgi} to deviate from a V^m-dependence (Fig. 10). This makes it difficult to correct for the Shockley saturation current I_{Si}. Therefore, since only measurements made below 0·5 V enter in the analysis, the uncertainty in the activation energy is greater. In Fig. 11 I_{rgi} corrected for the drift is plotted against $1/T$. We obtain:

$$E_r = 0{\cdot}63 \pm 0{\cdot}03 \text{ eV}$$

This means, that gamma irradiation also generates recombination centres, the level of which is in the middle of the energy gap.

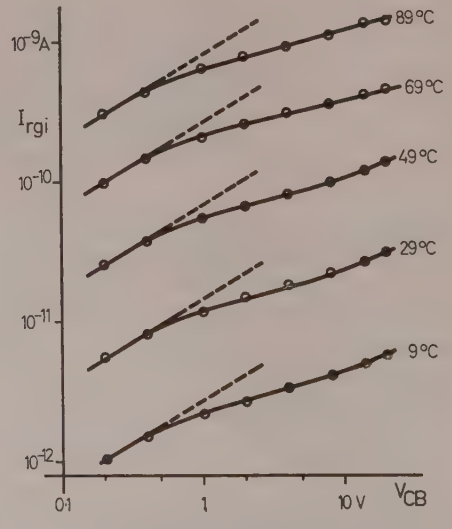

FIG. 10. Voltage characteristics of I_{rgi} (gamma irradiation).

A gamma irradiation induced level at the middle of the energy gap has never been reported. This is not surprising, because all other investigations were concerned with bulk irradiation damage. The level at $E_c - 0{\cdot}55$ eV, which VAVILOV[15] attributes to divacancies, cannot account for our results because of a large difference in annealing temperature.

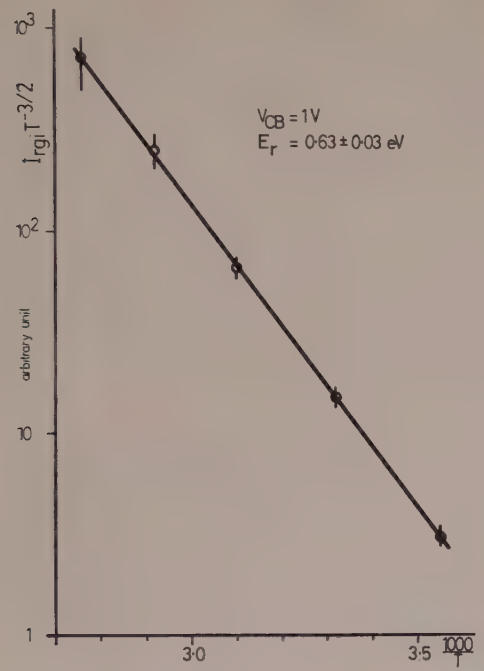

FIG. 11. Activation energy of I_{rgi} (gamma irradiation).

(d) I_B of gamma irradiated transistors

In measuring I_B only small voltages are applied. Therefore I_B shows no drift and can be determined accurately. I_{Bi} is the base current which is generated by gamma irradiation. It can be described by a similar exponential law as that describing the base currents of neutron irradiated transistors. I_{Bi} for different integrated gamma fluxes is plotted in Fig. 12. The analysis yields the following values:

$$n = 1{\cdot}80 \pm 0{\cdot}1 \qquad \text{(Fig. 13)}$$

$$E_b = 0{\cdot}68 \pm 0{\cdot}03 \text{ eV} \quad \text{(Fig. 14)}$$

n increases with integrated gamma flux reaching a value of 1·80 at saturation.

The values of n for neutron and gamma irradiated transistors are strikingly different. They correspond to the two values we found unirradiated transistors to group about. The same is true for the respective activation energies E_b. The values obtained correspond quite well to a relation

$$nE_b = E_{g0}.$$

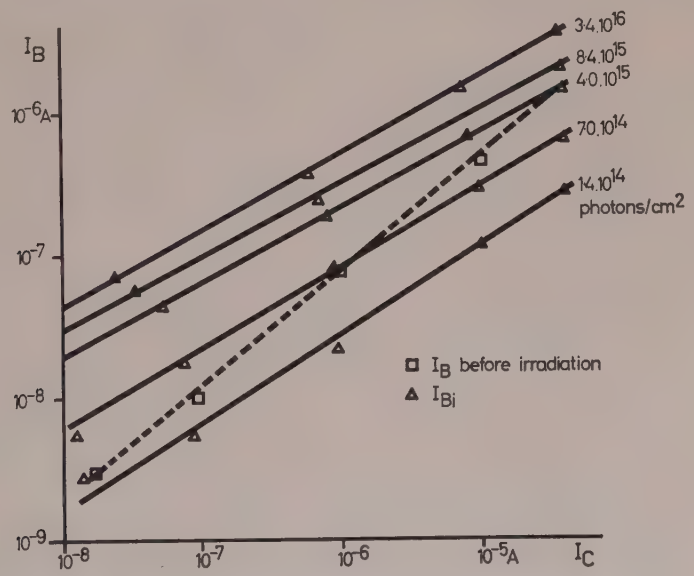

FIG. 12. Base current I_{Bi} with different integrated gamma fluxes.

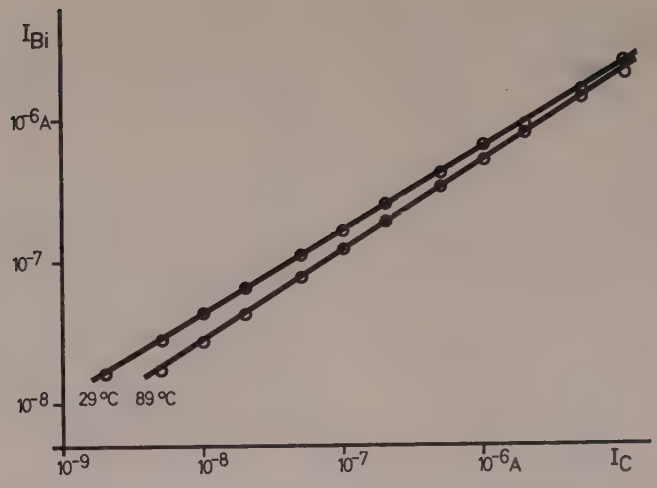

FIG. 13. Base current I_{Bi} (gamma irradiation) at different temperatures.

We believe, that two different effects are responsible for the base current I_B. It has been argued that transistor damage by gamma irradiation is mainly a surface effect. This strongly suggests, that the base current component with $n \geq 1{\cdot}60$ is a surface recombination current. It agrees with predictions of the SAH *et al.* theory to surface recombination.[11] Since we believe neutron damage to be located in the bulk of the transistor, we attribute the base current component with low n to the volume.

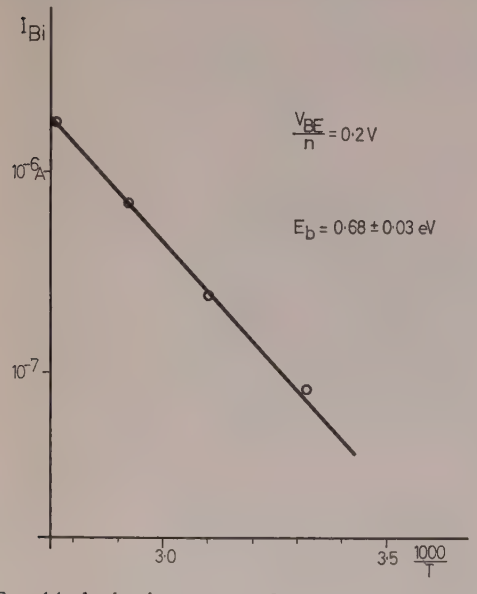

FIG. 14. Activation energy of I_{Bi} (gamma irradiation).

Our interpretation is supported by results of other authors. SAH[11] obtained base currents of mesa transistors (with unprotected surface) having $n \simeq 1{\cdot}80$ and of planar transistors with $n \simeq 1{\cdot}35$. IWERSEN *et al.*[16] were able to distinguish surface and bulk components of the base current. For the bulk current they obtained $n = 1{\cdot}12$, for the surface current $n = 1{\cdot}65$ and for the bulk recombination current $n = 2$. COPPEN and MATZEN[17] demonstrated, that currents with $n = 1{\cdot}65$ and $n = 2{\cdot}0$ originate at the surface. GOBEN and SMITS[18] have shown, that neutron irradiation generated base currents ($n = 1{\cdot}5 \pm 0{\cdot}3$) are bulk currents. IWERSEN *et al.*[16] have obtained values of E_a between 0·47 and 0·65 eV for base currents having $n \simeq 1{\cdot}8$.

The increase in base current corresponds to a reduction of the current transfer ratio h_{FE}. The high value of n obtained for gamma irradiated transistors means that gammas are especially detrimental to h_{FE} at low collector currents, while neutron irradiation affects the current transfer ratio more uniformly at all current levels.

5. ANNEALING

Investigations of the annealing behaviour have been undertaken on neutron and gamma irradiated transistors. The relative number, N_t/N_{t0}, of

recombination centres as a function of time and temperature was the desired quantity. I_{rgi} of neutron irradiated transistors (at 31°C) can be taken as a measure of the number, N_t, of recombination centres, because they are linearly related. However, if there are two kinds of recombination centres, the ratio of the reverse currents induced by each kind is not equal to the ratio of their number because of differences in recombination level and of capture probability.

For gamma irradiated transistors it has to be kept in mind, that the relation between I_{rgi} and N_t is non-linear (saturation). In the linear part of the $I_{rgi}-N_t$-relation I_{rgi} is too small to allow an annealing analysis. Since saturation cannot be explained no correction for the non-linearity is possible.

(a) Isochronal annealing

The general annealing behaviour has been investigated by isochronal annealing. Neutron irradiated transistors display two distinct annealing stages from 100 to 160°C and from 240 to 300°C (Fig. 15). Isochronal annealing of neutron radiation damage was also observed by changes in the

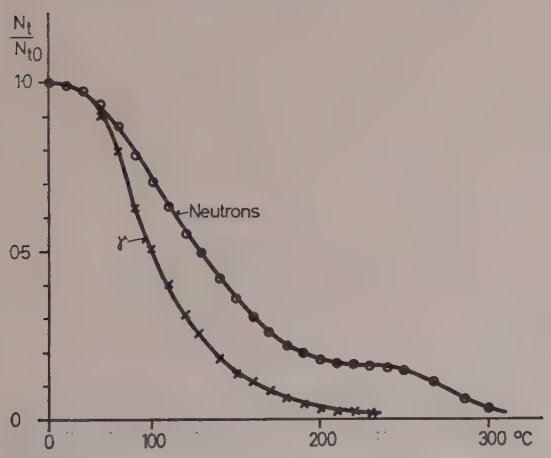

FIG. 15. Isochronal annealing curves of neutron and gamma irradiated transistors.

electron paramagnetic resonance spectra of homogeneous silicon crystals. Two stages were found in the same temperature regions. No information was obtained about the nature of the defect configurations from these EPR-spectra. Etching of the crystals did not change the spectra. Therefore the observed spectra are due to volume defects. This agreement further suggests that the defects we have observed in neutron irradiated transistors are a volume property.

Lifetime and Hall effect measurements of homogeneous crystals exhibit similar isochronal annealing curves.[19] A comparison of the annealing curves of homogeneous crystals and of transistors has been made in a previous paper.[20] *E*-centres (combination of a vacancy with a phosphor donor atom) likewise anneal at about 120°C. The observed stage has a somewhat steeper slope, however. The recombination level of the *E*-centre lies at $E_c-0{\cdot}4$ eV, in disagreement with our measurements. This could be explained in two ways. We may be observing a defect, which anneals at the same temperature as the *E*-centre. It is also conceivable that the recombination level of the *E*-centre has been shifted toward the middle of the energy gap due to the clustering of defects expected with neutron damage. Clusters may also explain the smoother annealing curve.

Isochronal annealing of gamma irradiated transistors proceeds in one stage between 80 and 160°C. The shape of the annealing curve was independent of the integrated gamma flux up to 10^{18} photons/cm^2 (10^9 r). Annealing of surface defects has not been investigated by other authors. Therefore no comparisons are possible.

(b) Isothermal annealing

A detailed investigation of the first stage in annealing neutron damage has been undertaken. The results of isothermal annealing of different transistors at six temperatures between 102 and 205°C are plotted in Fig. 16. A superposition of these curves by multiplying the time for each temperature with a characteristic factor is possible (Fig. 17). In Fig. 18 these factors have been plotted vs. $1/T$. This results in an activation energy for the annealing process:

$$E_a = 1{\cdot}53 \pm 0{\cdot}07 \text{ eV}$$

A similar value has been obtained by EDAGAWA *et al.*[21] for the annealing of gamma radiation damage. This value is rather high. Processes which take place in this temperature range normally have activation energies of about 1 eV. The activation energy of the annealing of *E*-centres is 0·94 eV.[22]

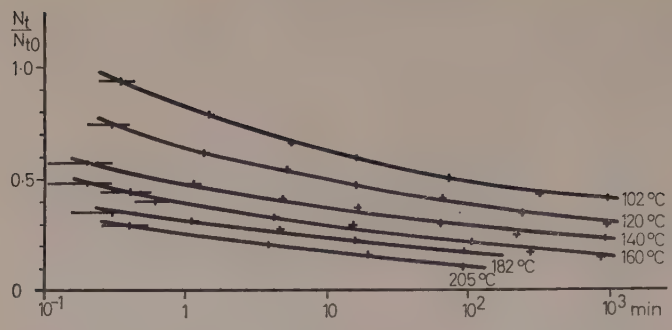

FIG. 16. Isothermal annealing curves (neutron irradiation).

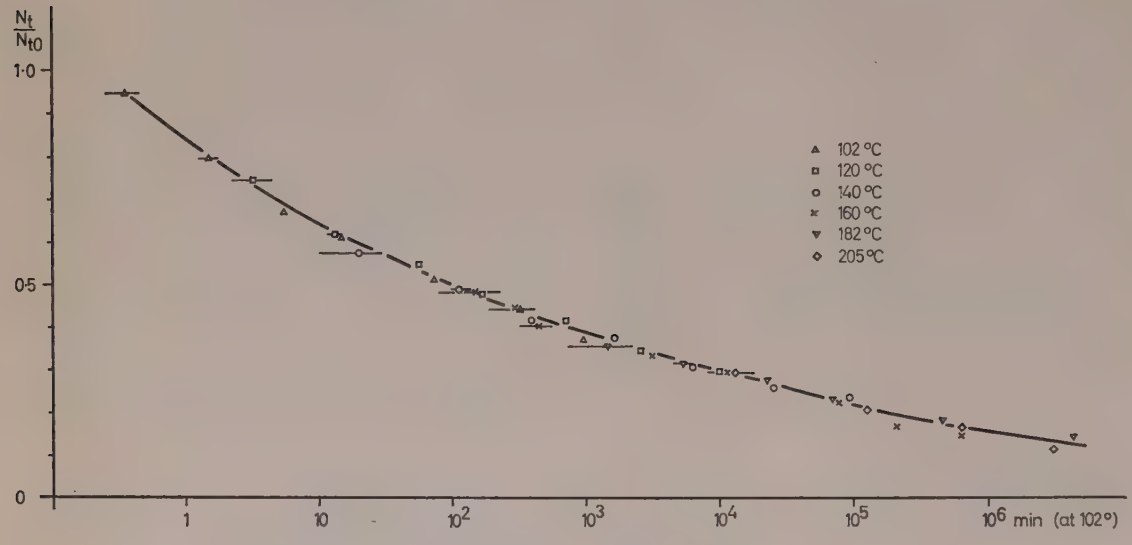

FIG. 17. Superposition of the isothermal annealing curves.

The curve which is obtained by superposition cannot be explained by ordinary annealing kinetics. For $t > 10^3$ min the curve can be matched by annealing kinetics of the eighth order

$$(\mathrm{d}N/\mathrm{d}t = \text{const.}N^8)$$

although this is physically unreasonable. Annealing of the neutron damage proceeds over many decades of time. Normally annealing is accomplished in two or three decades. No explanation has been found. Clusters again may be the reason for this strange behaviour.

Due to the drift, measurements on gamma irradiated transistors were not exact enough to allow a similar analysis. It can be said, however, that isothermal annealing after gamma irradiation proceeds somewhat faster than after neutron irradiation.

(*c*) *Improvement of transistors*

Transistors, which are gamma irradiated the first time, can be annealed to lower I_{CBO} values than before irradiation. Improvement is nearly complete after gamma fluxes of

$$5 \times 10^{15} \text{ photons/cm}^2 \ (6{\cdot}7 \times 10^6 \text{r})$$

and subsequent annealing for 1000 min at 300°C. After this treatment I_{CBO} normally decreases to 40 per cent of its original value and I_B to 65 per cent of the original value, hence the current

transfer ratio at small current densities is improved by 50 per cent. In some samples I_B goes through a minimum value during irradiation-annealing cycles. After this treatment the voltage characteristic of I_{CBO} shows a much sharper onset of breakdown than before. Breakdown voltage is increased by about 10 per cent.[20] This behaviour has been observed in most planar *npn* transistors, with the obvious exception of fast switching transistors. *pnp* transistors could not be appreciably improved by this method. The sensitivity to neutron irradiation was not changed by this treatment.

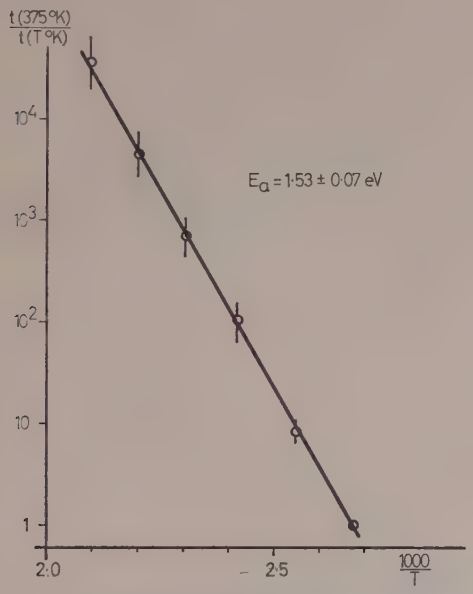

FIG. 18. Activation energy of the first annealing stage of neutron irradiated transistors.

This improvement can be explained by a change in surface potential caused by defects which do not anneal. This implies that a considerable amount of the I_{CBO} of unirradiated transistors is a surface current.

6. CONCLUSIONS

1. Neutron irradiation induces recombination centres in the bulk of the silicon. The reverse current I_{CBO} and the base current I_B increase linearly with integrated neutron flux. The recombination level of the induced defect is in the middle of the forbidden energy gap.

2. The effects of gamma irradiation are observed mainly on the surface. Damage curves saturate at about 30 times the pre-irradiation value of I_{CBO}. The recombination level of the induced defects is also in the middle of the forbidden energy gap. Moreover gamma irradiation introduces slow surface states, which cause a drift of the reverse current I_{CBO}.

3. The observed base currents have the form: $I_B = \text{const.} \exp(qV_{EB}/nkT)$. When the diffusion component of I_B is subtracted, the value of n is voltage and temperature independent. Different values of n have been found for neutron and gamma irradiation. For gamma irradiation $n = 1{\cdot}8$. This can be explained by surface recombination. After neutron irradiation an $n = 1{\cdot}27$ is found. This is attributed to a bulk effect which cannot be explained by any of the existing theories. The activation energies of the base currents correspond to the formula $E_b = E_{g0}/n$.

4. Gamma and neutron radiation damage can be completely annealed. Gamma radiation damage annealing proceeds in one stage at about 100°C. Annealing after neutron irradiation proceeds in two distinct stages at 120 and 270°C. For the first stage in neutron damage annealing an activation energy of $E_a = 1{\cdot}53 \pm 0{\cdot}07$ eV has been obtained.

5. *npn*-transistors can in many cases be improved by gamma irradiation-annealing cycles. The effect of this treatment is greater current transfer ratio at small current densities, smaller collector cutoff current, sharper onset of breakdown and higher breakdown voltage.

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CURRICULUM VITAE

Ich, MARTIN WALTHER LENZLINGER, von Riehen und St. Gallen, wurde am 30. November 1937 in Basel geboren als Sohn des Dr. Max Lenzlinger, Chemiker, und seiner Ehefrau Annie Lenzlinger geb. Wolfensberger, beide wohnhaft an der Niederholzstrasse 39 in Riehen.

Nach der Primarschule in Riehen besuchte ich von 1948 bis 1956 das Humanistische Gymnasium in Basel, das ich mit einer Matur Typus A abschloss. Darauf immatrikulierte ich mich an der Philosophisch-Naturwissenschaftlichen Fakultät der Universität Basel. Von September 1956 bis Juni 1957 hörte ich an der Wesleyan University (Middletown, Conn., USA) Vorlesungen in Physik, Mathematik und Chemie bei den Professoren Green, Coleman und Gomez-Ibanez. Nach diesem Amerika-Aufenthalt setzte ich das Physik-Studium an der Universität Basel fort. Im März 1959 bestand ich das Chemie-Nebenfachexamen und im Juni 1961 dasjenige in Mathematik. Von Anfang 1962 an arbeitete ich unter der Leitung von Herrn Prof. Dr. E. BALDINGER an einer Dissertation über die Bestrahlung von Silizium-Transistoren. Zur gleichen Zeit übernahm ich eine Assistentenstelle im Elektronik-Praktikum. Während dieser Jahre absolvierte ich den für die Beförderung zum Offizier nötigen Militärdienst.

Während meiner Studienzeit in Basel habe ich Vorlesungen und Praktika der folgenden Herren Professoren und Dozenten besucht:

in Physik: K. Alder, E. Baldinger, E. Baumgartner, F. Cerulus, W. Czaja, P. Huber, E. Miescher, P. Scherrer, H. R. Striebel, M. Verde, R. Wagner,
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in Mathematik: R. Conzelmann, M. Eichler, H. Huber, P. Leepin, A. Ostrowski,
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